# Probing Star Formation Timescales in Elliptical Galaxies

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**Abstract.**
In models of galaxy formation in a hierarchical Universe, elliptical galaxies form through the merging of smaller disk systems. These models yield a number of testable predictions if reliable techniques for determining the relative ages and compositions of the stellar populations of different galaxies can be found: 1) ellipticals in low-density environments form later than ellipticals in clusters, 2) more massive ellipticals form later, 3) more massive ellipticals form in dissipationless mergers from disk galaxies with low gas content. While colours and the Balmer line strengths of galaxies can be used to infer the average ages of the stellar populations of ellipticals, $\alpha$/Fe element ratios carry information about the timescale over which star formation took place. Here we present preliminary results from semi-analytic models for the distribution of Mg/Fe ratios in galaxies as a function of morphological type, luminosity and environment.

## 1. Hierarchical Clustering and the Formation of Ellipticals through Mergers

According to the standard theoretical paradigm, the structures observed in the Universe today were formed by the gravitational amplification of small perturbations in an initially Gaussian dark matter density field. Small scale overdensities were the first to collapse, and the resulting objects subsequently merged under the influence of gravity to form larger structures such as groups and clusters of galaxies. Galaxies formed within dense *halos* of dark matter, where gas was able to reach high enough overdensities to cool, condense and form stars.

The quiescent cooling of gas within a dark matter halo results in the formation of a rotationally-supported disk system at the centre of the halo. When halos merge with each other, a bound group of galaxies is produced. Dynamical friction will cause the orbits of the group members to erode over time, and the galaxies to spiral in towards the centre of the halo and merge. Galaxy-galaxy mergers are thus inevitable in this picture. N-body simulations have demonstrated that mergers between disk galaxies of near-equal mass result in the formation of remnant systems that are structurally very similar to observed elliptical galaxies (e.g. Barnes & Hernquist 1996).

Elliptical galaxies are a very homogeneous class of objects. Their stellar populations are old and in addition there is a well-defined correlation between colour and absolute magnitude that exhibits a remarkably small scatter (Bower, Lucey & Ellis 1992). There has been some doubt as to whether the old ages of ellipticals and the small scatter of the colour-magnitude relation can be explained in a scenario in which all ellipticals form by mergers of spirals. In order to address this issue, one must follow the formation and evolution of elliptical galaxies in the framework of the theoretical scenario described above.

## 2. Semi-Analytic Models of Galaxy Formation

In semi-analytic models of galaxy formation (see for example Kauffmann, White & Guiderdoni 1993; Cole et al 1994; Somerville & Primack 1999), an algorithm based on the extended Press-Schechter theory is used to generate Monte Carlo realizations of the merging paths of dark matter halos from high redshift to the present. These "merger trees" are specified for a chosen set of cosmological initial conditions and allow the progenitors of a present-day dark matter halo to be traced back to arbitrarily early times. Simple recipes are introduced to describe the cooling of gas within the halos, the formation of stars from the cold gas, feedback and heavy element enrichment from supernova explosions, and the merging rates of galaxies. The models are then coupled to a stellar population synthesis code in order to generate magnitudes and colours that can be compared directly with observational data.

If two galaxies of comparable mass merge, the stars of both objects are added together to create a bulge component. When a bulge is formed by a merger, the cold gas present in the two galaxies is transformed into stars in a "starburst" with a timescale of $10^8$ years. Further cooling of gas in the halo may lead to the formation of a new disk. The morphological classification of galaxies is made according their B-band disk-to-bulge ratios (Simien & de Vaucouleurs 1986). If $M(B)_{bulge} - M(B)_{total} < 1$ mag, then the galaxy is classified as early-type (elliptical or S0).

## 3. When, Where and How do Ellipticals Form in the Merger Picture?

It is important to define carefully what is meant by the "formation time" of an elliptical galaxy. The solid line in Fig. 1 shows the *average* star formation history of a present-day cluster elliptical galaxy. Results are shown for a high-density cold dark matter (CDM) cosmology with $\Omega = 1$, $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $\sigma_8 = 0.67$. As can be seen, most of the stars form at redshifts greater than 2. Because the stars form early, the small scatter of the observed colour-magnitude relation is not a problem for the model (Kauffmann 1996). The dotted line shows the distribution of the time of the last major merger. This is typically much later than the epoch at which the stars form; in this cosmology, many elliptical galaxies have their last major mergers at redshifts less than 1. The epoch of the last major merger also depends on the choice of cosmological parameters. In a low density model ($\Omega < 1$), the epoch at which structure forms is shifted to higher redshift. At z=1, more than 70% of present-day bright ellipticals are already present in a CDM model with $\Omega = 0.3$ and $\Lambda = 0.7$ (Kauffmann et al 1999), but most have not yet formed by $z \sim 2$. Finally, the formation time of an elliptical depends on its mass. More massive objects form later. Because the ratio of gas to stellar mass in galaxies decreases at late times, massive ellipticals form from gas-poor progenitors and form a smaller fraction of their stars in the merger-induced starburst (Kauffmann & Haehnelt, in preparation).

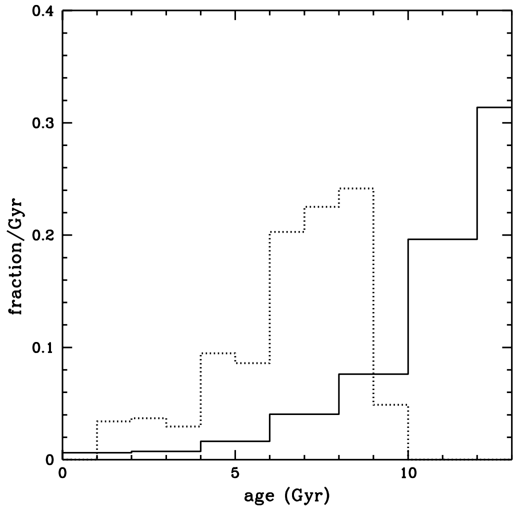


Figure 1. The solid line shows the *average* star formation history of a present-day cluster elliptical galaxy. The dotted line shows the distribution of the time of the last major merger. Results are shown for a high-density cold dark matter (CDM) cosmology with $\Omega = 1$, $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $\sigma_8 = 0.67$.

The probability of merging peaks in environments where the relative velocities between galaxies are comparable to their internal stellar velocity dispersions. In the semi-analytic models, bright ($> L_*$) elliptical galaxies are formed in dark matter halos with circular velocities in the range 250–350 km s$^{-1}$. These newly-formed ellipticals are *isolated* galaxies, with no bright companion within a radius of $\sim 1$ Mpc. Elliptical galaxies in groups and clusters are predicted to be significantly older than isolated ellipticals. In the standard CDM model, bright ellipticals in clusters and groups have $V$-luminosity weighted mean stellar ages that are 3–4 Gyr older than isolated ellipticals (Kauffmann 1996). The fact that galaxies form earlier in high density environments is a direct consequence of the statistical properties of the peaks of Gaussian random fields (Bardeen et al 1986) and is a prediction of *all* models based on the standard theory.

Another quantity of interest in the number of progenitor galaxies that merge together to form an elliptical. Kauffmann & Charlot (1998a) show that there is a weak trend in the number of progenitors as a function of the mass of the elliptical:

E galaxies with mass $10^{10} M_\odot$ typically form from 2–3 progenitors, whereas E galaxies more massive than $10^{11} M_\odot$ form from 5–7 progenitors. Because the number of progenitors only increases by a factor of $\sim 2.5$ over more than an order of magnitude in mass, these results also imply that massive Es also form from the merging of *more massive progenitors*. As discussed by Kauffmann & Charlot (1998a), this provides an explanation for why a correlation between mass and metallicity is preserved in a scenario where ellipticals form via the mergers of disk galaxies. In the models, massive disks are metal rich because the energy released from supernova explosions is not sufficient to eject enriched out of the galaxy. In low-mass disks, most of the metals escape into the surrounding halo and the galaxy is metal-poor. The massive, metal-rich disks then merge to form the most massive ellipticals.

## 4. Confrontation with Observations

The most direct test of the merger picture is the prediction that the global abundance of bright elliptical galaxies decreases at high redshift. In all currently popular theoretical models, the abundance of ellipticals decreases by at least a factor 3 by $z = 2$. Because ellipticals dominate the bright end of the $K$-band luminosity function, Kauffmann & Charlot (1998b) have suggested that $K$-band selected redshift surveys covering a wide area of the sky to a limiting magnitude of $K \sim 20$ would a very effective means of testing the merger scenario.

Testing the merger picture using ellipticals in clusters at high redshift is much more tricky because of the inherent biases predicted by the theory. In particular, the dense central regions of the most massive clusters always contain the oldest galaxies at any redshift. Kauffmann & Charlot (1998a) demonstrate that the apparent "passive evolution" observed for ellipticals in clusters out to $z \sim 1$ (Stanford, Eisenhardt & Dicksinson 1998) is quite consistent with the predictions of a high-density CDM model. The agreement comes about not because ellipticals are passively evolving, but because the observational selection procedure favours the oldest systems.

It is also possible to test the merger picture by looking for trends in the ages of elliptical galaxies as a function of environment. This test has been done at low redshift using a range of different stellar age indicators. Rose et al (1994), using a variety of different stellar absorption indices, and Mobasher & James (1996), using measurements of the CO absorption feature at 2.3mm, find evidence that ellipticals in low-density environments contain a substantial intermediate age population. Bernardi et al (1998), using the $Mg_2$ index, find a smaller difference between cluster and field ellipticals.

## 5. Element abundance ratios

While colours and Balmer line strengths of galaxies are used to infer ages of stellar populations, $\alpha$/Fe element ratios carry information about the timescale over which star formation took place. The reason for this lies in the delayed Fe enrichment from Type Ia supernovae, the progenitors of which are believed to be low-mass and hence long-lived binary stars. Models that incorporate this delay succeed in reproducing the abundance patterns in the solar neighbourhood (e.g. Greggio & Renzini 1983; Matteucci & Greggio 1986). Although we cannot measure abundance ratios in elliptical galaxies directly, the analysis of Mg and Fe line indices in ellipticals (Burstein et al 1984) using population synthesis models indicates that the ratio Mg/Fe in these objects is significantly super-solar by 0.2–0.3 dex (Peletier 1989; Worthey, Faber & González 1992). Subsequent studies confirm that this so-called $\alpha$-enhancement in the stellar populations of ellipticals extends out to the effective radius (Davies, Sadler & Peletier 1993; Carollo & Danziger 1994; Fisher, Franx & Illingworth 1995; Mehlert et al 1999). In a more quantitative study using $\alpha$-enhanced stellar tracks, Weiss, Peletier & Matteucci (1995) derive $0.3 \leq [\alpha/\mathrm{Fe}] \leq 0.7$ dex and in the bulge of our Galaxy, McWilliam & Rich (1994) find metal-rich stars having super-solar O/Fe and Mg/Fe ratios. Depending on the slope of the assumed initial mass function (IMF), such values require star formation timescales around $10^8$–$10^9$ years (e.g. Matteucci 1994; Thomas, Greggio & Bender 1999).

In models of hierarchical galaxy formation, star formation in ellipticals typically does not truncate after 1 Gyr, but continuous to lower redshift (Kauffmann 1996). It is therefore questionable if hierarchical clustering would lead to significantly $\alpha$-enhanced giant ellipticals (Bender 1997). Thomas et al (1999) discuss the abundance ratios associated with mergers of evolved galaxies, and show that a late merger is incapable in producing significantly super-solar Mg/Fe ratios in the stellar population. This result agrees qualitatively with a study by Sansom & Proctor (1998), who show that Mg/Fe ratios are lower when the object forms by subsequent mergers.

So far, semi-analytic models have not considered this constraint. In a preliminary study, Thomas (1999) demonstrated that the *average* star formation history (hereafter SFH) of cluster ellipticals predicted by the models (see Fig. 1) led to $[\mathrm{Mg/Fe}] \sim 0.04$ dex, a value well below the observational estimate. In the present paper, we use the *individual* SFHs given by the models to explore the distribution of Mg/Fe values in both cluster and field galaxies of different morphological types and luminosities.

The prescription of the chemical evolution is explained in Thomas (1999, and references therein). The chemical evolution code, particularly the supernova rates of both types, have been calibrated on the abundance patterns in the solar neighbourhood (Thomas, Greggio & Bender 1998). The semi-analytic SFHs are input directly into this code and include both quiescent star formation in the disk galaxy progenitors as well as the starburst triggered by the merger. Note that the chemical evolution models assume that galaxies evolve as single-body, "closed-box" systems and this is not the case in the hierarchical models, where supernova feedback effects are thought to be important in driving chemical evolution. Feedback effects could either drive the derived $\alpha$/Fe ratios up or down, depending on the relative efficiencies with which the products of Type II and Type Ia supernovae are expelled. We plan to explore this in detail in future work. We also assume a universal Salpeter IMF slope $x = 1.35$. In the following, $[\mathrm{Mg/Fe}] \equiv \log(\mathrm{Mg/Fe}) - \log(\mathrm{Mg/Fe})_\odot$ denotes the global element ratio in the *stellar population* of a individual galaxy. It should be emphasized that our plots do not show Mg/Fe ratios for the stars inside individual galaxies, but the variation obtained from one galaxy to another. We also only consider element ratios at redshift zero. The evolution of Mg/Fe with redshift is discussed in Thomas (1999). We show results for a cold dark matter power spectrum with $\Omega = 1$, $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, and $\sigma_8 = 0.67$.

### 5.1. Environmental effects

Fig. 2 shows the number distribution of Mg/Fe ratios among galaxies of different morphologies in environments of varying density. These distributions are computed by averaging over the galaxies in 15 halos with $V_c = 1000$ km s$^{-1}$ (clusters), 50 halos with $V_c = 500$ km s$^{-1}$ (groups), and 100 halos with $V_c = 300$ km s$^{-1}$ (small groups).

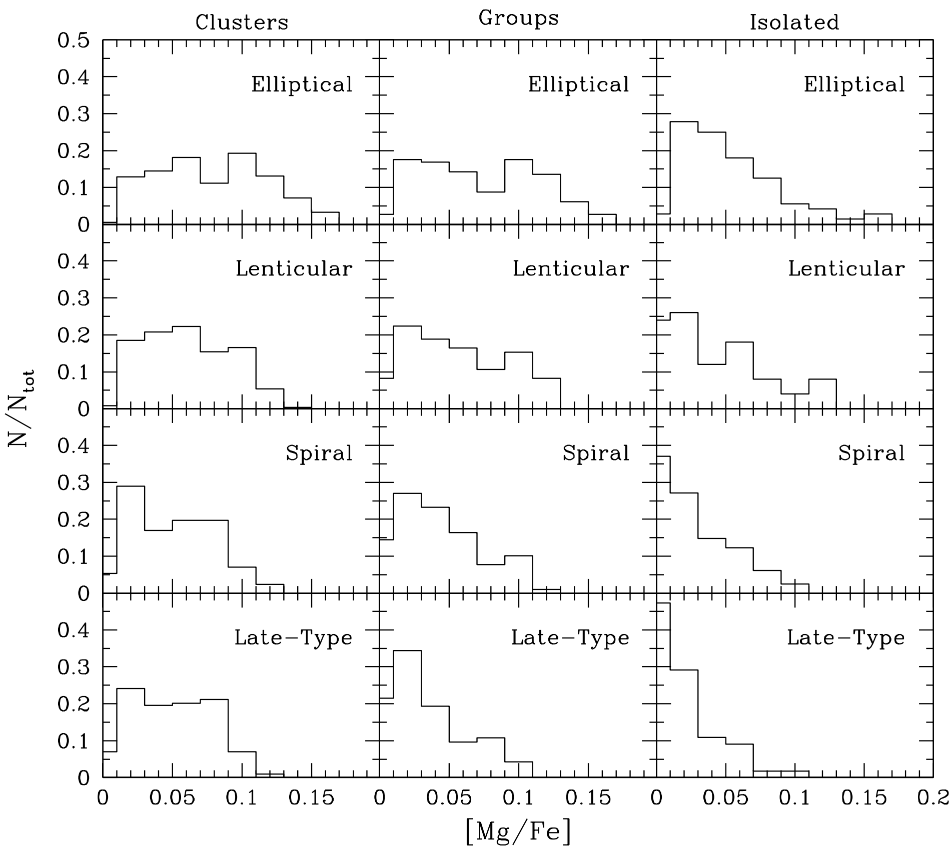


Figure 2. Number distribution of global Mg/Fe ratios among galaxies of different morphologies in environments of varying density.

The Mg/Fe values generally scatter between $0 \leq [\mathrm{Mg/Fe}] \leq 0.16$ dex, with a mean of 0.05–0.08 dex, significantly below the observed estimate quoted above. The spread in Mg/Fe results from the scatter in star formation timescales in the models (Kauffmann 1996). Late type galaxies experience more extended SFHs. As a result, these objects have younger stellar populations and exhibit lower Mg/Fe ratios, in qualitative agreement with observations. Although elliptical galaxies have the highest values of Mg/Fe, they still do not match the observed $\alpha$-enhancement. Only oldest galaxies, which form most of their stars in the first

1–2 Gyr, reach Mg/Fe close to the lower limit set by observations. Lenticular galaxies are expected to be slightly less $\alpha$-enhanced than ellipticals.

Galaxies in small halos form their stars over a more extended timescale than galaxies in clusters, where the supply of infalling gas is cut off as soon as the galaxy is accreted. As a result, lower Mg/Fe values are found for galaxies in small groups. In clusters, the formation is boosted towards higher redshift and more galaxies form on short timescales. Bright, isolated ellipticals are thus predicted to have lower Mg/Fe values than their counterparts in clusters (see also Thomas 1999). Kauffmann & Charlot (1998a) find that the $V$-light weighted age difference between bright cluster and "field" ellipticals is $\sim 1$ Gyr. This is in good agreement with the estimate by Bernardi et al (1998), who find that variations in zero-point and slope of the Mg-$\sigma$ relation of field and cluster ellipticals translate into an age difference of $1.2 \pm 0.35$ Gyr. Their study lacked information from Fe line indices and they could not determine whether there were trends in $\alpha$-enhancement from cluster to field. More work in this area would be very valuable.

### 5.2. Trends with luminosity

In Fig. 3 we plot the Mg/Fe values of model ellipticals as a function of $V$-magnitude for cluster ellipticals (left-hand panel) and isolated ellipticals (right-hand panel).

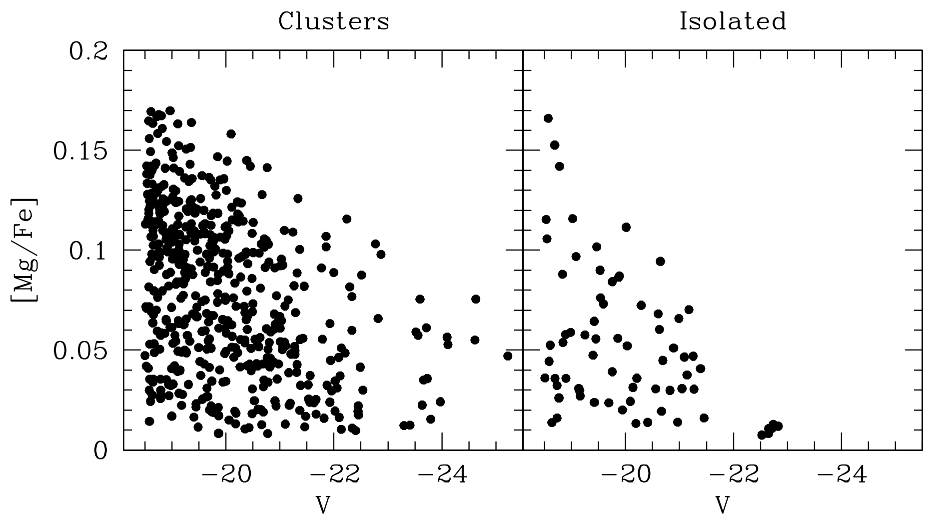


Figure 3. Global Mg/Fe in the model ellipticals as a function of absolute $V$-magnitude in a high density (left-hand panel) and low-density (right-hand panel) environment.

Faint ellipticals ($M_V > -20$) exhibit a scatter in Mg/Fe over a range from $0 - 0.17$ dex. Both the scatter and the median value decrease for brighter ellipticals because these objects form later and have younger mean stellar ages.

According to Kauffmann & Charlot (1998a), even though bright ellipticals are younger than faint ones, they still have redder colours because they are more metal-rich. Worthey et al (1992) claim, however, that the Fe index remains constant for elliptical galaxies of different mass. The tight correlation between Mg index and velocity dispersion $\sigma$ (Bender, Burstein & Faber 1993) then implies that Mg/Fe is higher in more massive ellipticals. This is in clear disagreement with the trend shown in Fig 3. Note that if the Fe index is a reasonable tracer of metallicity, the results of Worthey et al imply that both the Mg-$\sigma$ relation and the colour-magnitude relation may simply be an effect of an increase in $\alpha$-element enhancement as a function of the mass of the elliptical. As we have shown, this is not easily accommodated in hierarchical models, because it is the *low mass* ellipticals that form on short timescales. Another interpretation is that Fe indices are not viable metallicity indicators (González 1993), and the super-solar $\alpha$/Fe ratios in luminous ellipticals actually result from an Fe deficiency (Buzzoni, Mantegazza & Gariboldi 1994). It may be possible to achieve this in models where metal ejection is treated in detail.

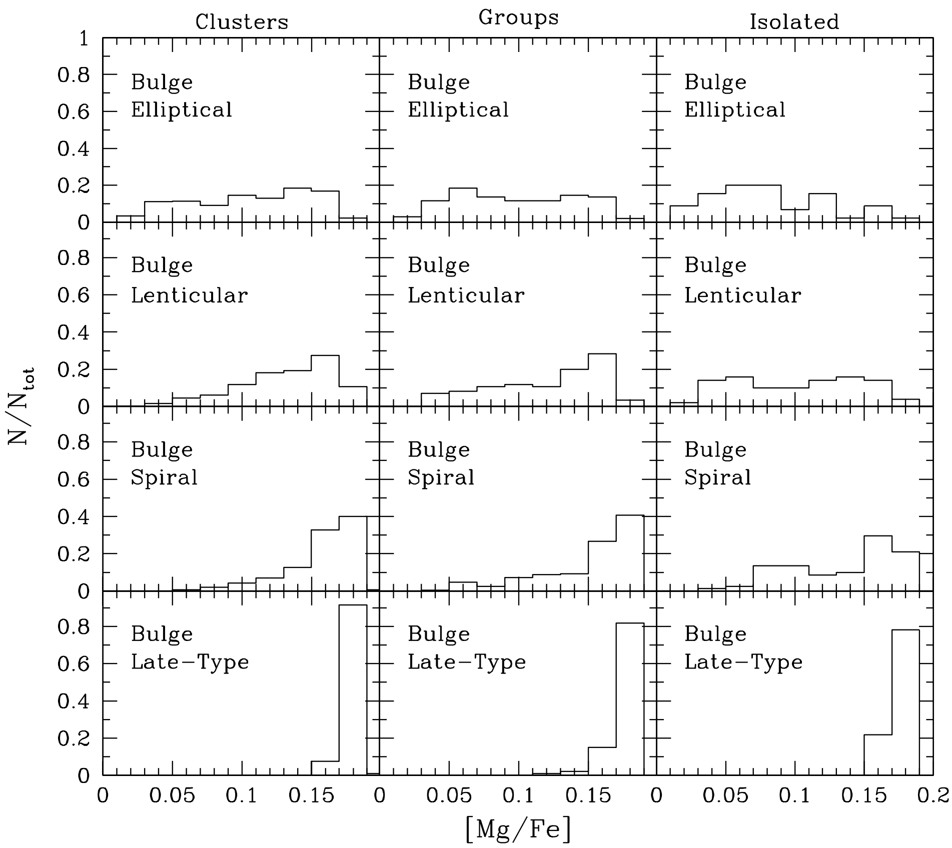


Figure 4. Number distribution of Mg/Fe ratios among bulges in galaxies of different morphologies in environments of varying density.

### 5.3. Bulges

Bulges are the first spheroids to form in major mergers at high redshift (Kauffmann 1996). Depending on the amount of gas accreted subsequently, these spheroids may become the bulges of spiral galaxies. As discussed previously, the classification into morphological type is made according to disk-to-bulge ratios, so even ellipticals have a minor disk component.

Fig. 4 shows the distribution of Mg/Fe among the *bulge components* of galaxies of different types in a variety of environments. The drop of the Mg/Fe ratio from high to low density environment is less pronounced in the bulge component. Another striking result is that the bulges of late-type galaxies are more $\alpha$-enhanced and exhibit a much smaller scatter in Mg/Fe. This result is expected in a scenario where the bulge forms first and the disk slowly accretes over a Hubble time. If the bulge is formed from the disk, one would not expect to see such an effect. It would be interesting to study Mg and Fe line indices in the bulges of galaxies of different morphological type in order test some of these trends (see Trager, Dalcanton & Weiner 1999).

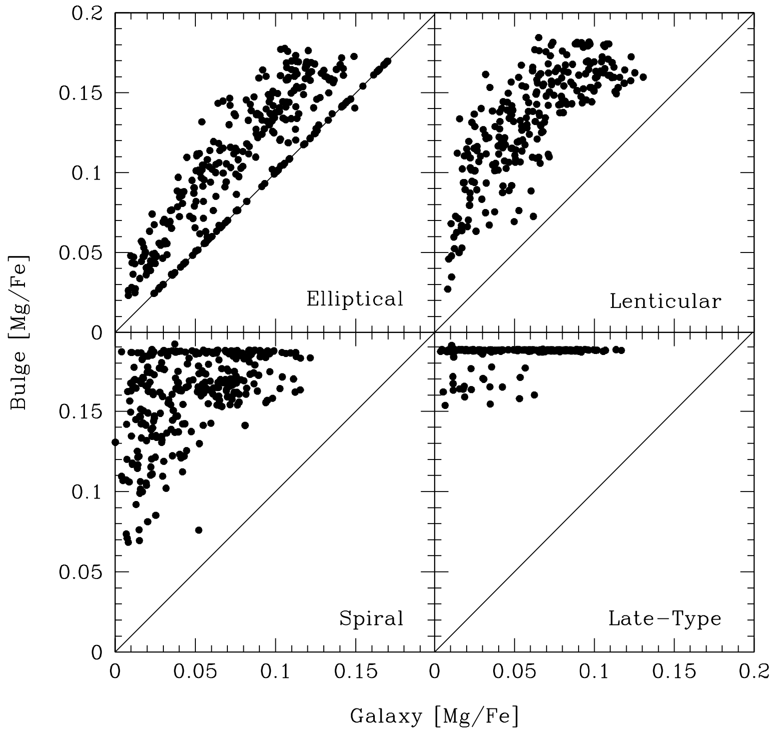


Figure 5. Mg/Fe ratios in bulges of different galaxy types as a function of the global Mg/Fe in the respective galaxies. Rich cluster environment.

In Fig. 5 we plot the global value of Mg/Fe versus the Mg/Fe of the bulge component for different types of galaxies in a rich cluster. The value of Mg/Fe is always higher in the bulge than it is on average and this difference increases for late type galaxies. This result is interesting because the bulge component is expected to be more spatially concentrated, which implies a radial gradient in Mg/Fe inside the galaxy. In elliptical galaxies, observations indicate Mg/Fe to be constant with radius inside the half-light radius (Worthey et al 1992; Davies et al 1993; Fisher et al 1995).

### 5.4. Caveats and future improvements to the models

1) Although we have adopted the SFHs predicted by the semi-analytic models, we have not yet treated chemical evolution in consistent way. Inclusion of metal ejection will allow us to study abundance ratios in the intra-cluster medium (e.g. Mushotzky et al 1996)

2) Indices are measured close to the centres of the galaxies where the starburst population may dominate the light (Barnes & Hernquist 1996). The quantities calculated in this work are for the global stellar population. We also plan to explore two-component models where chemical evolution in the burst is treated separately.

3) We assumed a universal Salpeter IMF. It would be interesting to study the effect of flattening the IMF of the stars that form in the burst, which would increase production of $\alpha$-elements (see Thomas 1999).

4) A more quantitative comparison between model predictions and observables can be obtained by transforming the calculated Mg/Fe element ratios to line indices on the basis of Mg/Fe-dependent fitting functions and stellar tracks.

5) The choice of cosmology has an impact on the SFHs and therefore also on the resulting abundance ratios. In particular, in low-$\Omega$ universes star formation is pushed towards higher redshift yielding higher Mg/Fe.

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